Ionosphere Monitoring using Galileo: First Results and Future Prospects

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Abstract

We present first results of using GIOVE-B data for determining the total electron content (TEC) over Europe. Furthermore, we present a multi-GNSS calibration technique which allows determining the inter-frequency biases along with calibrated TEC.

Introduction

The first two satellites of the European Global Navigation Satellite System (GNSS) Galileo, GIOVE-A and GIOVE-B, have been launched in 2005 and 2008, respectively (GIOVE – Galileo In Orbit Validation Element), cf. [REF_1]. The transmitted signals provide a unique opportunity to demonstrate the capability of using Galileo for monitoring ionospheric behaviour and related space weather effects.

Data Base

Utilising the E1-E5 (or E1-E6) code and phase observable of GIOVE, we derive the relative slant total electron content (TEC). In order to calibrate these relative measurements, the E1-E5 inter-frequency biases (IFB) have to be determined.

In order to solve for the IFBs, we impose the condition that the sum of the satellite IFBs per GNSS is zero. As a result, we are able to determine the IFB of GIOVE Sensor Stations (GESS) and inter-system IFBs between GIOVE and GPS. In particular, this provides the possibility of studying the stability of the GIOVE IFBs. The results of these different TEC data retrievals are compared.

To demonstrate the procedure, we used data from May 25, 2009 from the European GNSS ground stations listed in Table 1. Their locations are shown in Figure 1

Station	Location	Longitude / °E	Latitude /°N	GPS	GALILEO	GLONASS
gien	Torino, Italy	7.639	45.015	√	√	-
gnor	Noordwijk, The Netherlands	4.419	52.218	√	√	-
gkir	Kiruna, Sweden	20.968	67.857	√	√	-
karl	Karlsruhe, Germany	8.411	49.011	√	-	√
leij	Leipzig, Germany	12.374	51.354	√	-	√
onsa	Onsala, Denmark	11.926	57.395	√	-	√
ptbb	Braunschweig, Germany	10.460	52.296	√	-	-

Table 1: *Locations and coordinates of used GNSS ground stations.*

The GIOVE data were obtained from http://www.giove.esa.int and the GPS/GLONASS data from IGS data centers (e.g. http://igscb.jpl.nasa.gov/). In order to use the GIOVE data, we have developed a decoder for the Septentrio Binary Format [REF_2]. The most challenging part was to decode the GIOVE navigation message, since it is given as the pure string of bits broadcasted by GIOVE. What prevented us from using GIOVE-A was that its navigation message appeared to be empty, i.e. some of the data fields contained 0s instead of valid data.

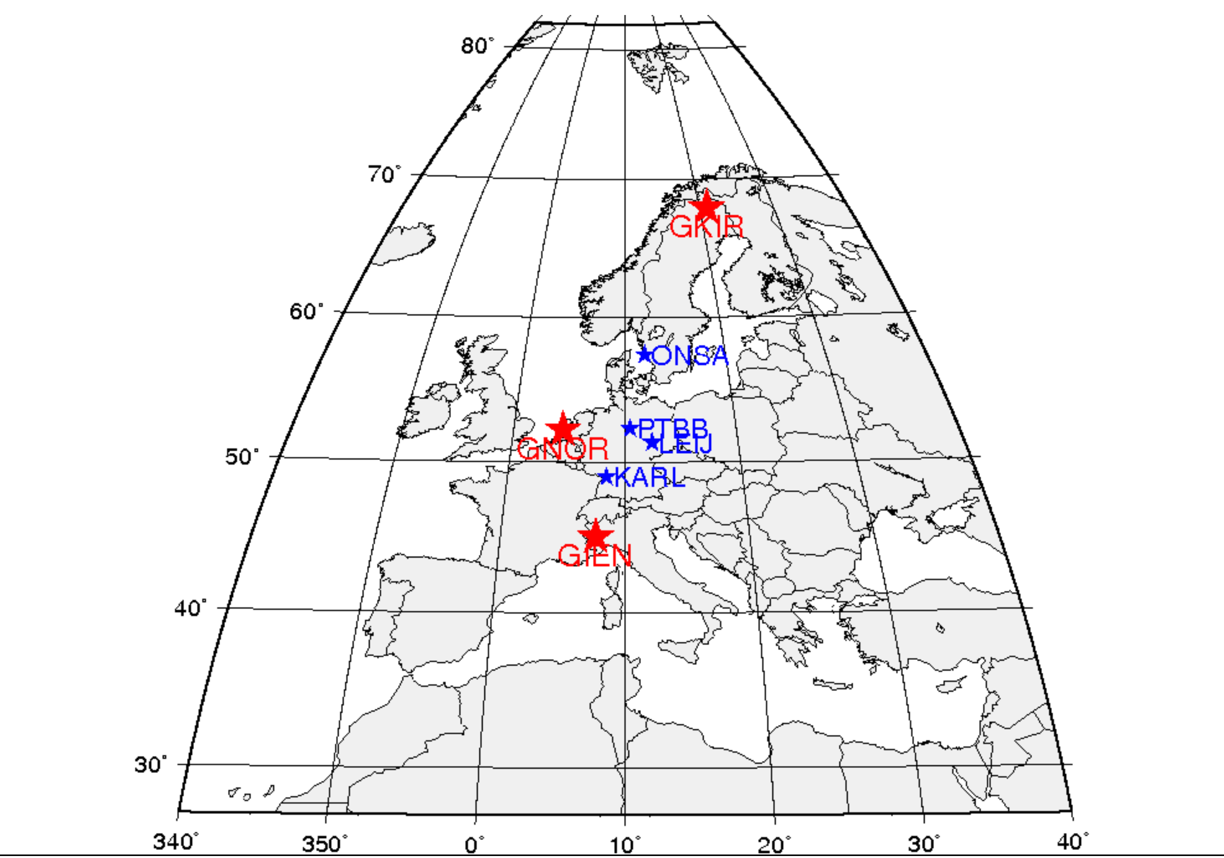

Figure 1: *Geographical distribution of used GNSS ground stations. Red – GESS, blue – IGS*

Measurement Analysis and Discussion

We used the L1 and L2 code- and phase observables of GPS ground stations [REF_6], the L1 and E5 code- and phase observables of the GESS [REF_5] and dual-frequency data of GLONASS ground stations [REF_7]. Note that we use the GIOVE pilot signals when available.

The ionosphere error derived from code measurements is given by

$$I_{code}(f_1) = \frac{f_2^2}{f_2^2 - f_1^2}\{P(f_2) - P(f_1)\} \quad (1)$$

$I_{code}(f_1)$	ionosphere error at frequency f_1 derived from code measurements [m]
$P(f_1)$	code observable at frequency f_1 [m]
$P(f_2)$	code observable at frequency f_2 [m]

The ionosphere error derived from phase measurements is given by

$$I_{phase}(f_1) = \frac{f_2^2}{f_2^2 - f_1^2}\{L(f_1) - L(f_2)\} \tag{2}$$

$I_{phase}(f_1)$	ionosphere error at frequency f_1 derived from phase measurements [m]
$L(f_1)$	phase observable at frequency f_1 [m]
$L(f_2)$	phase observable at frequency f_2 [m]

Note that the reversed sign in (1) relative to (2) is due to the difference of phase and group speed for the propagation of electromagnetic waves in the ionospheric plasma.

The data pre-processing includes the following steps:

- Compute elevation/azimuth,
- Compute latlitude/longitude of ionosphere pierce points, applied is a single-layer approximation of the ionosphere fixed at height 400 km.
- Smoothing of I_{code} with I_{phase} in order to reduce code-multipath noise

The input for the ionosphere and bias estimation are the smoothed I_{code} measurements, converted to TECU (1TECU=16.2 cm at L1 GPS frequency).

For the bias and ionosphere estimation, data of all 9 GNSS ground stations listed in Table 1 is collected over 24 hours and then fed into a least-squares algorithm using the following Ansatz

$$I = \sum_{i=1}^{12} M_i c^i + b_{ground} - b^{sat} \tag{3}$$

I	smoothed ionosphere errors [TECU}
M_i	ionosphere model basis functions [1]
c^i	ionosphere model coefficients [TECU]
b_{ground}	bias of ground station [TECU]
b^{sat}	bias of satellite [TECU]

We use a linear model for the ionosphere over Europe with 12 coefficients which is a simplified version of the NTCM model [REF_3]. Since the model coefficients are geometry-dependent, we can separate the model from the constant biases and solve for the unknowns $\{c_i, b_{ground}, b^{sat}\}$. Since b_{ground} and b^{sat} are subtracted from each other in (3) they are not uniquely determined. In order to fix this ambiguity we demand that

$$\sum_{j \in Sats} b^{sat,j} = 0 \textit{ per GNSS system} \tag{4}$$

These constraints are implemented by using Lagrange multiplications which yield additional pseudo-measurements. Note that since there is only one GALILEO satellite available, its bias is set to zero by the constraint (4).

As a result, we obtain the IFBs listed in Table 2. The IFBs for GIOVE-B are consistently big for the three ground stations which indicate that the GIOV-B bias is big. Also, the RMS for GIOVE is bigger than for GPS and GLONASS: this is a consequence of the fact that GIOVE-b was visible only a short time on that day.

Station Name	GNSS System	Bias / TECU	RMS Bias / TECU
E_gien	GALILEO	-2386.24	2.02
E_gkir	GALILEO	-2390.18	1.96
E_gnor	GALILEO	-2393.80	2.17
G_gien	GPS	-74.45	0.52
G_gkir	GPS	-76.41	0.77
G_gnor	GPS	-82.19	0.56
G_karl	GPS	10.18	0.53
G_leij	GPS	1.05	0.56
G_onsa	GPS	11.05	0.59
G_ptbb	GPS	23.96	0.61
R_karl	GLONASS	14.43	0.64
R_leij	GLONASS	22.73	0.66
R_onsa	GLONASS	16.15	0.63

Table 2*: Inter-frequency biases for May 25, 2009. Each GNSS system has its own IFB, hence stations receiving more than one GNSS system have one bias per GNSS system.*

As Figure 2 clearly demonstrates, the GIOVE derived TEC values are in good agreement with TEC from other stations involved in the calibration procedure. All contributing stations and satellite systems are listed up in Table 1. Since the data were obtained under low solar activity conditions, the day-time TEC level remains rather low. The noontime bite-out effect observable under summer-time conditions can nicely be seen.

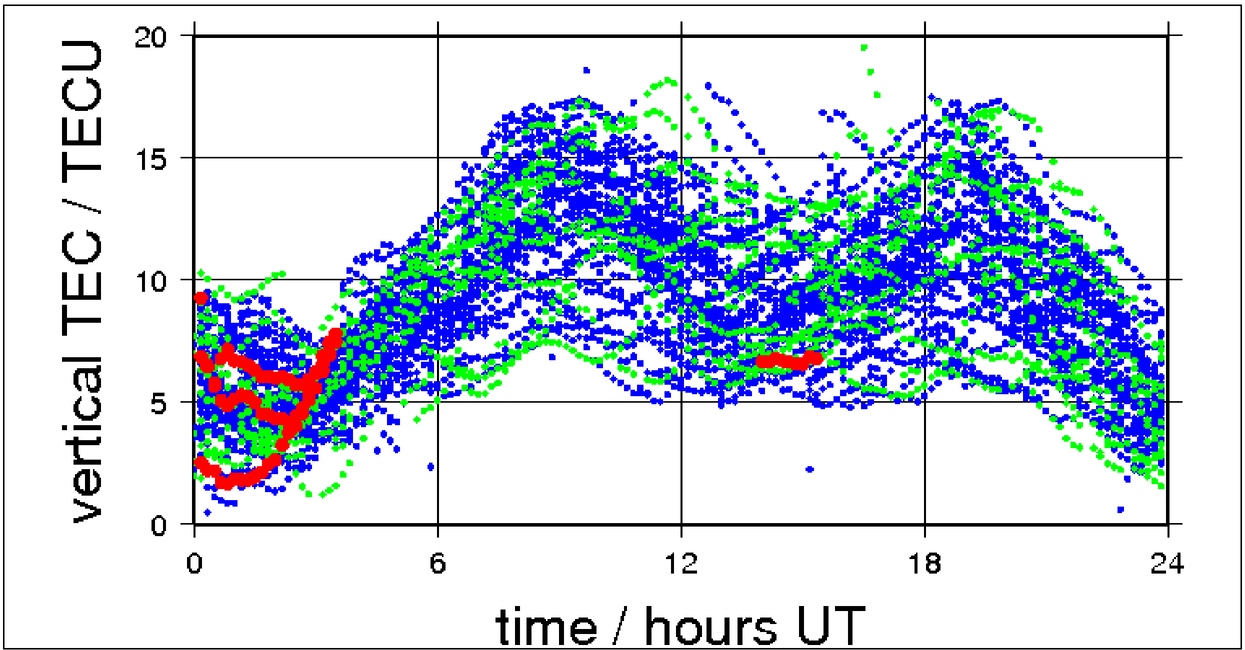

Figure 2*: Comparison of calibrated vertical TEC on May 25 2009. blue – GPS, green – GLONASS, red – GIOVE-B*

An independent check was made with TEC map reconstructions over Europe (http://www.kn.nz.dlr.de/daily/tec-eu/) routinely made in DLR since 1995 using GPS measurements from the European IGS station network [REF_3]. Comparing the two TEC reconstructions over Europe, we obtain the histogram shown in Figure 3. The two data sets are in good agreement with a low mean deviation of well under one TECU and standard deviation of 2.5 TECU.

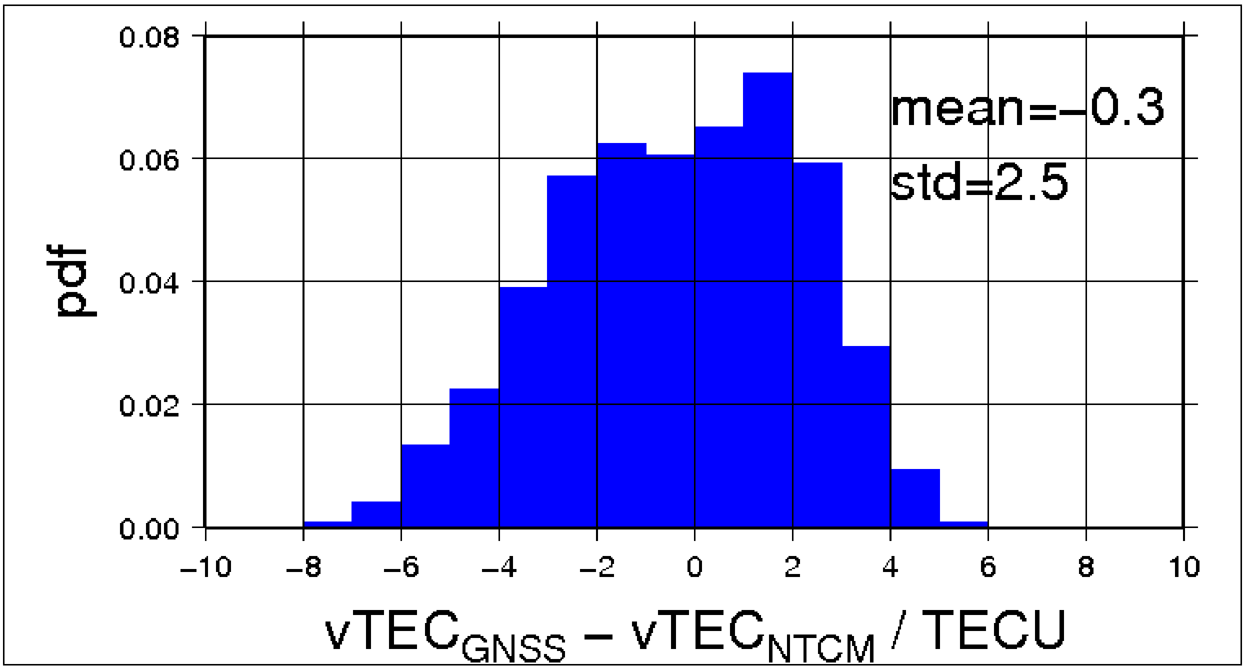

Figure 3*: Comparison of GALILEO+GPS+GLONASS-derived calibrated vertical TEC with vertical TEC obtained by IGS measurements, cf. http://www.kn.nz.dlr.de/daily/tec-eu/*

Conclusions

The GIOVE-B derived TEC data agree very well with routine TEC reconstructions made in parallel using GPS measurements at IGS ground stations over Europe. The measurements on 25 May 2009 were performed under low solar activity and quiet geomagnetic activity conditions.

Since we used only one GIOVE satellite, its inter-frequency bias was set to zero. However the Galileo-biases obtained for the three used GESS indicate that the GIOVE-B satellite bias is quite large.

In the future, when Galileo is fully operational, the number of TEC measurements increases substantially due to the availability of at least three GNSS: GPS, GALILEO and GLONASS. Since these GNSS have different orbit characteristics, the observations at the sky above a ground station are more evenly distributed than ever before. Thus, new and/or improved possibilities for monitoring and modelling the ionosphere arise which allow us to study and monitor both, the regular ionospheric variations and space weather events in greater detail than ever before. It is planned to include Galileo satellite data into the regular ionospheric service provided by DLR via the project Space Weather Application Center Ionosphere [REF_4].

Acknowledgements

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References

[REF_1] http://www.giove.esa.int

[REF_2] GAL-TN-IND-I-1010, Septentrio Binary Format description http://www.giove.esa.int/Sep_bin_form.pdf

[REF_3] Jakowski, N., TEC Monitoring by Using Satellite Positioning Systems, Modern Ionospheric Science, (Eds. H.Kohl, R. Rüster, K. Schlegel), EGS, Katlenburg-Lindau, ProduServ GmbH Verlagsservice, Berlin, pp 371-390,1996

[REF_4] SWACI – Space Weather Application Center Ionosphere, http://swaciweb.dlr.de

[REF_5] GIOVE A+B SIS ICD, http://www.giove.esa.int/images/userpage/ESA-DTEN-NG-ICD02837_GIOVE-A+B_PublicSISICD_1-1.pdf

[REF_6] GPS ICD200c, www.navcen.uscg.gov/pubs/gps/icd200/default.htm

[REF_7] GLONASS ICD Version 5.0, www.glonass-ianc.rsa.ru/i/glonass/ICD02_e.pdf